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Analyses of Riding Tests for Evaluating the Wet Braking Performances of Bicycles

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Institute for Materials Research
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ANALYSES OF RIDING TESTS FOR EVALUATING THE WET BRAKING PERFORMANCES OF BICYCLES

Leonard Mordfin

ABSTRACT

The Consumer Product Safety Commission has expressed interest in the development of a riding test method for evaluating the braking performances of bicycles in wet weather. In this report three different testing approaches for caliper-braked bicycles are examined using kinetic analyses, a review of the literature, and an evaluation of available domestic and foreign test results. On the basis of the findings it is recommended that the riding test include the intentional wetting of both the bicycle brakes and the test pavement; the former to obtain meaningful results and the latter to enhance the repeatability of the test results. A tentative pass-fail criterion is also offered, based on a maximum wet stopping distance which, at this time, appears to be generally attainable only with bicycle wheels having aluminum-alloy rims. Error analyses of the test methods are presented.

Key Words: Bicycles; brakes, bicycle; braking, wet; error analysis; friction, brake; friction, tire/pavement; kinetics, bicycle; measurements, bicycle braking; road tests; standards, bicycle safety; test methods, bicycle; wet braking.

CONTENTS

1. INTRODUCTION

The current bicycle safety regulations promulgated by the U. S. Consumer Product Safety Commission (CPSC) include requirements governing braking performance in normal (dry) weather[1].* These requirements specify a riding test** wherein the stopping distance, which a bicycle is capable of achieving, is measured under stipulated test conditions. Some of these test conditions are based on analyses reported in NBSIR 75-786 [2], which were carried out by the National Bureau of Standards (NBS) on an earlier version of the safety regulations [3].

Requirements for a similar riding test method are being developed by the International Organization for Standardization (ISO)[4]. In addition, ISO is pursuing a modification of the test method which would allow bicycle braking performance to be evaluated under simulated wet-weather conditions. CPSC has also expressed interest in this approach, and this report is intended to provide the Commission with some basic analyses of the kinetics and the errors involved in riding tests for measuring the braking performances of bicycles under wet conditions.

This study was carried out for the NBS Office of Consumer Product Safety at the request of CPSC.

1.1 Terminology

Since this report is an extension of NBSIR 75-786, the terminology and definitions developed therein are also used here. Some of these are explained here; for other relevant definitions, and for the rationales behind them, the reader is advised to consult the earlier report.

For the sake of specificity, this study is principally concerned with a typical bicycle having handlever-operated caliper brakes on both wheels, and marginal braking capability. The essential characteristics of the <u>typical bicycle</u> [2] are reproduced in Table 1.

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* Numerals in square brackets refer to similarly numbered references listed in Section 7 of this report.

** The term "riding test" is used in this report to distinguish it from dynamometric or other performance tests which are usually conducted in a laboratory. The preferred term, "road test", is not used in order to avoid confusion with the specific road test which is cited in the CPSC regulations for a different purpose.

Table 1. Characteristics of the Typical Bicycle [2]

Mass of bicycle	18 kg	(39.7 lb)
Mass of bicycle frame	14 kg	(30.9 lb)
Mass of bicycle wheel	2 kg	(4.4 lb)
Wheel diameter	660 mm	(26.0 in)
Wheel base	1000 mm	(39.4 in)

Coordinates of the center of gravity of the bicycle with an average 68.1-kg (150-lb) rider:

Distance aft of the front wheel axis	600 mm	(23.6 in)
Distance above the pavement	850 mm	(33.5 in)

A bicycle exhibits marginal braking capability [2] when it is brought to a stop over a distance of exactly 4.57 m (15.0 ft) under the standard test conditions. (This is the pass-fail criterion specified by the bicycle regulations [1] for dry conditions.)

The standard test conditions [2] include: an average 68.1-kg (150-lb) test rider; an initial speed of 24 km/h (15 mph); the application of 178-N (40-lbf) forces to the handbrake levers; and a dry, clean, level, paved test course which offers a uniform coefficient of friction of 0.75 at the tire/pavement interface of a locked bicycle wheel. (These conditions are identical to those specified in the bicycle regulations [1] except that the latter permit both heavier riders and a range of friction coefficients.)

An average test rider is one of average physical characteristics who provides an average reaction time of 0.15 seconds [2].

Reaction time is the interval between the instant at which the rider first begins actuating the handbrake levers and the instant at which the prescribed force levels are reached [2].

1.2 Scope

Within the scope of a riding test under wet conditions, several alternatives are available. The pavement may be wetted, the wheel rims (which are engaged by the caliper brake pads) may be wetted, or both the pavement and the wheel rims may be wetted. Sections 2, 3 and 4 of this report analyze each of these three options, in turn, on the basis of theoretical considerations and available laboratory-type test data. The results of actual riding tests are then examined in Section 5.

2. ANALYSIS: WET PAVEMENT, DRY BRAKES

2.1 Kinetic Analysis

Consider, first, an idealized riding test in which the pavement is wet but the brakes are dry. The presence of the water changes the friction coefficient at the tire/pavement interfaces from that which prevailed under dry conditions. For a typical bicycle which has marginal braking capability under dry conditions, the effect of the friction coefficient on stopping distance is illustrated in Figure 1. The curve plotted in the figure was calculated from Equations (20), (25) and (28) of NBSIR 75-786.

The curve is characterized by a discontinuity in the slope at a friction coefficient of 0.547. Under the standard test

conditions this point represents the changeover, for the front wheel, from locked-wheel skidding (on the left) to rolling without slipping (on the right). The rear wheel skids without rolling throughout the range of coefficients shown. Note that variations of the friction coefficient above the changeover point do not cause major changes in stopping distance. However, for friction coefficients less than 0.547, small variations of the coefficient cause large variations of stopping distance.

In view of the desirability of achieving repeatable test results, it is clearly of interest to know whether the wet friction coefficients which are likely to be encountered in actual test situations are smaller or larger than 0.547.

2.2 Tire/Pavement Friction Coefficients

Friction coefficients for bicycle tires on wet pavements have not been widely reported in the literature. However, data obtained with automotive and aircraft tires provide some guidance, particularly in view of the fact that tread patterns do not exert a significant influence on the wet braking capabilities of bicycles [5].

Mechanical engineering handbooks state that for rubber tires a friction coefficient of 0.7 is commonly used with dry asphalt and a value of 0.8 with wet asphalt [6, 7]. However, more thorough treatments of the subject, based on test results obtained with automobiles, reveal that the situation is not nearly so well defined, and that the friction coefficients are generally lower when wet than when dry. According to the British Road Research Laboratory [8], for example, wet asphalt and concrete pavements typically offer friction coefficients of 0.5 to 0.7, but values as low as 0.1 have occasionally been observed. On the other hand, a value of 0.8 is considered to be characteristic of a good dry road surface.

A review by Whitt and Wilson [5] suggests that friction coefficients of the order of 0.1 are generally indicative of icy, rather than wet, pavements. They report that for motor cars on concrete or asphalt pavements, typical friction coefficients range from about 0.8 to 0.9 under dry conditions and from about 0.4 to 0.7 when wet.

Obviously, the observed variations in wet friction coefficients result, in part, from differences in the pavement surface characteristics. However, even for a specific road surface there is no single value of wet friction coefficient that can be assigned to it. Rather, as described below, it has been found that the wet friction coefficient varies with the speed of the vehicle, the depth of the water, the ambient temperature, and the cleanliness of the surface. For this reason, the friction values

cited above, while helpful in a general sense, do not provide the guidance that is needed to estimate wet friction coefficients in specific situations.

It has been well established, from tests with both automotive and aircraft tires, that wet friction coefficients increase with decreasing speed [5,8,9,10]. Thus, the friction coefficient may be expected to vary continuously during a braking test from a given initial speed. However, it has been shown that stopping distances may be calculated with reasonably good accuracy by using, as an effective coefficient, that which corresponds to two-thirds of the initial speed [8]. Thus, to calculate the stopping distance of a bicycle from 24 km/h (15 mph), it would be appropriate to use the tire/pavement friction coefficient which prevails at 16 km/h (10 mph).

The effect of water depth is more complex. Slightly dampened pavements offer friction coefficients which are significantly less than those obtained with dry pavements. However, as the water depth is increased there is sometimes a tendency for the effective friction coefficients to rise, due to fluid drag. Thus, for example, with aircraft tires on a concrete test runway which offered a dry coefficient of approximately 0.4 at 16 km/h (10 mph),* reductions of the order of 0.1 were obtained with less than 0.3 mm (0.01 in) of water. But with depths of 5 to 8 mm (0.2 to 0.3 in) the measured coefficients were higher than this, approaching the dry values [9]. A smaller increase in friction with increasing water depth was observed in another, similar, investigation. In that work the average friction coefficient at 16 km/h (10 mph)* was found to be 0.56 on a damp runway with no visible standing water, and 0.59 when the runway was dammed and flooded to a depth of 6.4 mm (0.25 in) [10].

It would appear that if riding tests are to be performed on wet pavements it would be desirable to maintain a uniform water depth. In this connection, it has been reported that on a well-drained road, during and after a rain, the thickness of the water film in a typical instance may vary between 0.5 and 0.08 mm (0.02 and 0.003 in) [8]. Perhaps with this in mind, the ASTM method for measuring the skid resistances of highways calls for a uniform water depth of 0.5 mm (0.02 in) [11]. Unfortunately, NBS researchers were forced to conclude, after several years of experimentation, that a completely satisfactory pavement-wetting system does not appear to be available at this time [12].

The effect of temperature on wet friction coefficients has not been studied extensively, but one investigation showed changes of almost 0.05 for only a 10°C (18°F) change in temperature [8].

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*These data were interpolated from test results at lower and higher speeds.

It is intuitively obvious that mud, loose aggregate and similar kinds of dirt can affect the coefficient of friction at tire/pavement interfaces. Quite appropriately, therefore, the CPSC and ISO test methods require that the road surfaces be clean [1,4]. It is, perhaps, not quite so obvious, however, that the tenacious rubber deposits, which accumulate on pavements from braking tests, can also influence the friction coefficients. Typical results from one investigation [13], for example, showed that on a runway with significant rubber deposits the average dry and wet friction coefficients were 1.0 and 0.7, respectively. After the deposits were removed the dry and wet coefficients were 0.9 and 0.8, respectively. It would appear that allowing rubber deposits to build up on a test pavement could adversely affect the reproducibility of test results within a given laboratory.

2.3 Systematic Errors

The CPSC test method for dry braking requires that the coefficient of friction at the tire/pavement interfaces be less than 1.0, yet large enough to avoid front-wheel locking [1]. For the typical bicycle this establishes the permissible range as 0.547 to 1.0. (A typical value of 0.75 was used for calculation purposes [2].) For test pavements which meet these requirements under dry conditions, it must now be estimated what the applicable friction coefficients are when the pavements are wet.

The data reviewed above suggest that when the dry coefficient is low, the wet coefficient tends to be only about 0.1 lower. However, when the dry coefficient is high, the reduction due to wetting is sometimes greater. An extreme example of the latter, from the work of Mortimer and Ludema*, shows a 50-percent reduction, from 0.70 for a dry pavement to 0.35 for the same pavement when wet. On the basis of these observations it does not appear to be inconsistent to expect the range of wet friction coefficients of bicycle test pavements to extend from about 0.4 to 0.8, with a typical value (corresponding to 0.75 when dry) of about 0.6. This selection of a relatively broad range of wet coefficients is supported by data which reveal that a smooth concrete surface and a fine-textured asphalt surface, both of which exhibited dry coefficients of approximately 0.75, showed wet coefficients that differed by about 0.2 [8]. Furthermore, the most sophisticated measuring techniques, when applied to a series of specially prepared highway test surfaces, revealed a distribution of wet coefficients ranging from about 0.57 to about 0.83 at 16 km/h (10 mph) [15].

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*As cited in Reference 14.

The differences in stopping distances obtained on different test surfaces, as a result of differences in wet friction coefficients, represent systematic errors which inhibit the lab-to-lab reproducibility of test results. The stopping distances which correspond to the probable range of wet friction coefficients can be determined from Figure 1 for the typical bicycle with marginal braking capability:

Wet coefficient of friction	Stopping distance m	(ft)
0.4 (min.)	6.23	(20.4)
0.6 (typ.)	4.65	(15.3)
0.8 (max.)	4.55	(14.9)

Note that the changes in stopping distance due to variations of the friction coefficient above 0.6 are relatively small, but that low coefficients produce large increases in stopping distance. These data can be combined to indicate an average systematic error of the order of ±0.84m (±2.8 ft) about the typical stopping distance.

2.4 Random Errors

There is reason to expect that the wet coefficient of friction of a bicycle test pavement may change from one test to the next even though precautions are taken to keep the pavement clean. Five measurements made with a single bicycle on a single wet test surface revealed tire/pavement friction coefficients ranging from 0.48 to 0.61 [16]. While some of this variation was probably only apparent, due to variabilities in rider reaction times, some real friction variations are probably unavoidable, due to changes of temperature and water depth. A variability of ±0.05, centered about the mean wet friction coefficient of the surface, would appear to be a reasonable estimate.

If the mean coefficient is on the flat part of the curve in Figure 1, the resulting variations in stopping distance are not serious. However, if the mean coefficient is less than 0.547, then the test-to-test variations in stopping distance are significant. For example, if the mean wet coefficient is 0.45, then a variability of ±0.05 in the coefficient produces a variation of approximately ±0.58m (±1.9 ft) in stopping distance. The effects of this test-to-test variability are fortunately mitigated by the CPSC requirement that only the average of four test results need be reported [1]; the average of four independent measurements has twice the precision of a single measurement [17].

3. ANALYSIS: DRY PAVEMENT, WET BRAKES

3.1 Kinetic Analysis

Now consider an idealized riding test in which the caliper brake pads and the wheel rims are wet but the tires and the pavement are dry. The presence of water at the brake surfaces reduces the brake friction and thereby results in increased stopping distances.

Note that the important parameter here is not simply the wet coefficient of friction at the brake surfaces but, rather, the ratio of the wet coefficient of friction to the dry coefficient of friction. Even a braking system with a low friction coefficient can be made effective by providing a suitably high mechanical advantage in the braking system linkage. This mechanical advantage is fixed by the design of the bicycle and, unless the wet-to-dry brake friction ratio is close to unity, a bicycle designed to provide adequate dry braking will exhibit inadequate braking performance under wet conditions. Conversely, a bicycle designed for adequate wet braking will be overly sensitive under dry conditions if the friction ratio is low. Excessive dry braking capability introduces a pitchover hazard. Thus, for good braking performance, both wet and dry, it is desirable that the brake friction ratio be as close to unity as possible.

For a typical bicycle which has marginal braking capability under dry conditions, the effect of the brake friction ratio, wet to dry, is shown in Figure 2. The curve plotted in the figure was calculated from Equations (1), (15), (20) and (28) of NBSIR 75-786.

The curve is somewhat similar in appearance to that shown in Figure 1 in that it contains a discontinuity in the slope. In this case, however, the discontinuity represents a changeover in the mode of braking for the rear, rather the front, bicycle wheel. The changeover occurs at a brake friction ratio of 0.422. For lower ratios the rear wheel rolls without slipping while for higher ratios it skids without rolling. The front wheel rolls without slipping throughout the range of brake friction ratios plotted.

Since small variations in the brake friction ratio below the changeover point cause rather large changes in stopping distance, it is of interest to ascertain whether the brake friction ratios in actual tests are below or above the changeover point.

3.2 Brake Friction Coefficients

The coefficient of friction between caliper brake pads and bicycle wheel rims depends, of course, on the brake pad and wheel rim materials and on their surface conditions, as well as on whether they are wet or dry. Handbook-type information specifies dry coefficients of 0.35 to 0.40 for asbestos-fabric brake material against a cast iron brake drum [7], 0.3 to 0.5 for leather to metal [5], and approximately 0.7 for brake-lining materials against cast iron or steel [5]. A more thorough study of dry friction in caliper brakes was provided by a bicycle manufacturer who tested brake pads of ten different materials against a steel bicycle wheel rim [18]. Using the data from these tests it may be shown by calculations that the dry coefficients of sliding friction ranged from 0.22 for the least effective brake material to 0.61 for the most effective. These two materials were both proprietary products. Three different kinds of rubber brake pads exhibited coefficients of 0.48.

Several investigations of bicycle brake pad materials have been conducted to evaluate the reduction in the friction coefficients that are produced by wetting. In one of these [19], seven brake pad materials were examined against a plated steel wheel rim and the results were not entirely consistent with those reported above. In this case, rubber brake pads were found to offer the highest dry friction coefficient (0.95) and the lowest wet friction coefficient (0.05). The brake friction ratios, wet to dry, varied from a low of 0.05 for rubber to a high of 0.50 for a proprietary product.

The difference between the dry coefficients for rubber brake pads, as given in the above two paragraphs, may stem from differences in the shapes, compositions or surface conditions of the brake pads or the wheel rims. This is evident from the results of a set of tests, involving twenty different kinds of rubber brake pad materials, which was performed on a dynamometer bench [20]. Comparative stopping distances, wet and dry, were measured. Since rider reaction times do not enter into this type of measurement, the observed stopping distances are inversely proportional to the brake friction coefficients. Thus, it may be shown that the brake friction ratios, wet to dry, varied from 0.29 to 0.44 for the twenty materials against a smooth steel wheel rim, and from 0.32 to 0.61 for the same materials against a smooth aluminum-alloy wheel rim.

Another set of dynamometer tests, involving four different kinds of unidentified brake pad materials, was carried out using a striated steel rim [21]. In this case the brake friction ratios, wet to dry, varied from only 0.13 to 0.19. Intuitively, it would seem that the introduction of striations,

or other kinds of roughening, onto wheel rim surfaces would tend to provide increased brake friction coefficients. It has been reported, for example, that rust on the wheel rims tends to raise the friction coefficients [22], and that unplated wheel rims give 20-percent shorter braking distances than chrome-plated rims under wet conditions [23]. This matter is addressed further in Section 5.1.

3.3 Error Analysis

The scant data available on wet-to-dry brake friction ratios show values ranging from 0.05 to 0.61. With such a wide range it is difficult to select a "typical" value which can be used as the basis for an error analysis that might be applicable to a typical bicycle. For want of a more meaningful approach, the safety standard for motorcycles [24] has been used as guidance. This standard requires the wet stopping distance not to exceed 2.25 times the dry stopping distance. For bicycles, the dry stopping distance from an initial speed of 24 km/h (15 mph) is required to be no more than 4.57m (15.0 ft) under the standard test conditions [1]. If, therefore, the wet stopping distance is taken as 2.25 this value, or 10.28m (33.7 ft), then Figure 2 shows that the applicable wet-to-dry brake friction ratio is 0.25.

As pointed out above, the brake friction ratio depends on the brake pad and wheel rim materials, and these, of course, are independent of the laboratory conducting braking performance tests. Hence, for a given bicycle, it is not expected that there would be any systematic error that would be attributable to variabilities in brake friction from one lab to another. This, of course, assumes that the testing procedure will have been adequately standardized with respect to the means by which wetting will be achieved.

On the other hand, it may be expected that there would be random variations in the brake friction ratio from test to test, due to minor changes in water film thicknesses, wear, and cleanliness conditions. It would seem that a random variation of approximately ±0.05, about the average brake friction ratio, would be reasonable. This would introduce variations of the order of ±2.0m (±6.6 ft) about an average 10.28-m (33.7-ft) wet stopping distance. Such test-to-test variations are disturbingly high, even when mitigated by a requirement that only the average of four test results need be reported.

4. ANALYSIS: WET PAVEMENT, WET BRAKES

4.1 Kinetic Analysis

When both the pavement and the brakes are wet, reductions in the friction coefficients may be expected at both the tire/pavement interfaces and the brake surfaces. According to the ISO working group which is concerned with wet weather braking, "...the water film between the [brake] block and the rim [is] by far the most important factor having a much larger effect on the stopping distance than water on the road braking surface," and the group decided, therefore, that a dry surface would be used for all wet braking tests [25]. At least one foreign delegate to this group expressed a dissenting opinion, namely, that the coefficient of friction at the road surface is the most important parameter [26].

Performance calculations, based on Equations (1), (15), (20) and (28) of NBSIR 75-786, tend to support the majority ISO opinion. The effects of both friction sources, on the wet stopping distance under otherwise standard test conditions, is shown in Figure 3 for the typical bicycle which exhibits marginal braking capability when dry. The location of the discontinuity in the curve, in this case, is seen to depend upon the friction coefficient μ at the tire/pavement interfaces. For low values of the wet-to-dry brake friction ratio both wheels of the bicycle roll without slipping and the stopping distance is independent of μ. For higher brake friction ratios the rear wheel skids without rolling and the front wheel rolls without slipping. In this situation the stopping distance is influenced by both the brake friction ratio and the tire/pavement friction coefficient, with the former having the greater effect. Another discontinuity appears in the curve for $\mu = 0.4$ at a brake friction ratio of 0.63. For brake friction ratios above this value both bicycle wheels skid without rolling and the stopping distance is independent of the brake friction ratio.

4.2 Error Analysis

An estimate of the errors involved in testing with both wet pavement and wet brakes can be obtained by combining the error estimates which were developed for wet pavements (Sections 2.3 and 2.4) and for wet brakes (Section 3.3). Using a square-root-of-the-sum-of-the-squares approach, it is found that the combined systematic error is ±0.84m (±2.8 ft) and the combined random error is ±1.8m (±5.9 ft). The systematic error influences the lab-to-lab reproducibility and the random error affects the degree of reproducibility within a single laboratory.

(These error estimates do not include the variabilities in rider reaction times and rider masses which would be expected to be the same in wet braking tests as in dry braking tests.)

4.3 Test Method Considerations

Almost all of the riding test methods, which have been used or proposed to evaluate the wet braking capabilities of bicycles, have called for the wetting of the brakes, with or without simultaneous wetting of the pavement. These methods include:

a. Riding the bicycle through a long water trough prior to commencement of the braking test [27, 28].

b. Spinning the wheels in a water trough prior to the test [29].

c. Spraying the brakes and rims prior to the test [30, 31].

d. Spraying the wheels and the pavement prior to the test [15].

e. Spraying the brakes and rims during the test [25].

f. Spraying the brakes and rims during the test and conducting the test on a previously moistened pavement [32].

g. Spraying the bicycle and the pavement both prior to and during the test [33].

While the differences between these various testing approaches would appear to offer difficulties in comparing test results, this is not entirely the case. Even without any conscious intent to moisten the test pavement, but only the brake surfaces, it is likely that some water will flow onto the tires from the wheel rims, and penetrate the tire/pavement interface. As shown in Section 2.2, very little moisture need be present at the interface in order to change the friction coefficient from the dry value to the wet value. In fact, photographs show considerable water accumulation on the pavement surface after a number of tests have been run [27]. For this reason, tests involving wet brakes and dry pavement are actually only idealizations; in reality, wet brake tests should generally be considered as involving wet pavements as well.

It has been suggested that when brakes are wetted before rather than during tests, small-wheeled vehicles may show better braking performance because more wheel revolutions for a given speed tend to wipe more water off [31]. However, tests have shown that when wet brakes are applied with full pressure, and no additional water is added, the brake friction coefficient does not <u>begin</u> to recover until the wheel has completed at least

four revolutions and frequently many more [19]. For a bicycle with 26-in (660-mm) wheels this represents a minimum distance traveled of 8.3 m (27 ft). Substantially longer distances (40 m (30 ft) or more) are required in order to attain 90-percent recovery of the brake friction coefficient [19].

4.4 Discussion

The kinetic analysis (Section 4.1) showed that the presence of water at the brake surfaces is generally more detrimental to braking performance than water at the tire/pavement interfaces. On this basis it is recommended that road tests for evaluating the wet braking performances of bicycles should include the wetting of the brake surfaces.

The considerations discussed in Section 4.3 suggest that it is also of no major significance whether the water is introduced onto the brake surfaces before or during the test so long as these surfaces are wet when the brakes are applied. In fact, it would seem that all of the seven test methods listed in Section 4.3 might be expected to yield essentially equivalent results if applied to a given bicycle, assuming that all of the other aspects of the testing procedure are the same. This observation provides the basis for the following section of this report, which examines the results of riding tests carried out with a variety of wetting practices to evaluate the wet-braking performances of bicycles.

5. TEST RESULTS

Table 2 presents a compilation of available riding test data on the wet braking performances of bicycles.* The test methods used were those cited in Section 4.3. Where directly comparable data were acquired under dry conditions, these are included in the table.

5.1 Effects of Wheel Rim Material

The effects of the wheel rim material can be assessed from the test results shown in Table 2 where different rims were used on the same bicycles. Considering, first, rims which had been neither serrated** nor embossed, it is found that

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* Additional data, received more recently, involve some rather specific test conditions and will be addressed in a subsequent report.

** Strictly speaking, serration is an edge treatment. However, when applied to wheel rims, the term is commonly used in the bicycle industry to describe a surface treatment.

Table 2. Results of Wet (and Dry) Riding Tests[a]

Caliper brakes, front and rear.
Initial speed, 24 km/h (15 mph).[b]

Bike No.[c]	Wheel rim material[d]	No. of tests		Average stopping distance[e]				Ratio,[f] wet/dry	Ref.
		dry	wet	dry		wet			
				m	(ft)	m	(ft)		
101	NA	3	3	7.92	(26.0)	41.24	(135.3)	5.2	27,34
102	Cr	5	6	3.81	(12.5)	56.69	(186.0)	14.9	27,30
102	emb[g]	5	5	3.35	(11.0)	16.34	(53.6)	4.9	27,30
103	NA	-	6	-	-	21.82	(71.6)	-	31
104	NA	-	3	-	-	25.76	(84.5)	-	31
105	NA	-	4	-	-	34.81	(114.2)	-	31
106	NA	-	3	-	-	29.57	(97.0)	-	31
107A	Cr	3	2	9.47	(31.1)	27.24	(89.4)	2.9	35
107B	Cr	4	2	4.53	(14.9)	19.10	(62.7)	4.2	35
107B	Al	5	3	4.52	(14.8)	7.90	(25.9)	1.7	35
107C	Cr	NA	NA	4.21	(13.8)	13.33	(43.7)	3.2	35
107C	Al	NA	NA	4.38	(14.4)	6.28	(20.6)	1.4	35
108A	SS	10	10	3.43	(11.3)	10.40	(34.1)	3.0	33
108A	emb SS	10	10	4.10	(13.5)	11.75	(38.5)	2.9	33
108A	Al	10	10	4.16	(13.6)	6.06	(19.9)	1.5	33
108A	emb Al	10	10	3.56	(11.7)	6.42	(21.1)	1.8	33
108A	Cr	10	10	3.05	(10.0)	10.12	(33.2)	3.3	33
108A	emb Cr	10	10	4.36	(14.3)	12.20	(40.0)	2.8	33
108B	SS	10	10	5.00	(16.4)	13.90	(45.6)	2.8	33
108B	emb SS	10	10	4.53	(14.9)	13.70	(44.9)	3.0	33
108B	Al	10	10	5.10	(16.7)	12.78	(41.9)	2.5	33
108B	emb Al	10	10	4.54	(14.9)	12.78	(41.9)	2.8	33
108B	Cr	10	10	3.94	(12.9)	12.91	(42.4)	3.3	33
108B	emb Cr	10	10	4.70	(15.4)	12.76	(41.9)	2.7	33
109	steel	-	6	-	-	12.49	(41.0)	-	32
109	Al	-	6	-	-	6.65	(21.8)	-	32
110	steel	-	6	-	-	21.37	(70.1)	-	32
111	Cr	-	5	-	-	13.1	(43.)	-	16
112A	Cr	-	5	-	-	31.1	(102.)	-	16
112A	Al	-	15	-	-	9.1	(30.)	-	16,36
112A	serr Al	-	10	-	-	7.3	(24.)	-	36

(continued)

Bike No.(c)	Wheel rim material(d)	No. of tests dry	No. of tests wet	Average stopping distance(e) dry m	dry (ft)	wet m	wet (ft)	Ratio,(f) wet/dry	Ref.
112B	Cr	-	5	-	-	17.7	(58.)	-	16
113A	steel	-	5	-	-	17.90	(58.7)	-	37
113B	steel	-	5	-	-	10.43	(34.2)	-	37
114A	steel	-	5	-	-	11.82	(38.8)	-	37
114B	steel	-	5	-	-	10.93	(35.9)	-	37
115A	steel	-	5	-	-	22.54	(74.0)	-	37
115B	steel	-	5	-	-	24.19	(79.4)	-	37
116	steel	-	NA	-	-	24.4	(80.)	-	38
116	Al	-	NA	-	-	9.1	(30.)	-	38
116	serr Al	-	NA	-	-	18.0	(59.)	-	38
117A	steel	50	50	5.70	(18.7)	38.3	(125.)	6.7	26,39
117B	steel	50	50	6.64	(21.8)	39.8	(131.)	6.0	26,39
118A	steel	15	15	5.29	(17.4)	38.52	(126.4)	7.3	26,39
118B	steel	15	15	5.78	(19.0)	40.08	(131.5)	6.9	26,39
119A	steel	50	50	5.11	(16.8)	21.79	(71.5)	4.3	26,39
119B	steel	50	50	6.68	(21.9)	21.40	(70.2)	3.2	26,39
120A	steel	50	50	5.48	(18.0)	65.90	(216.2)	12.0	26,39
120B	steel	50	50	6.34	(20.8)	29.82	(97.8)	4.7	26,39
121A	steel	50	50	4.50	(14.8)	55.52	(182.5)	12.3	26,39
121B	steel	50	50	4.97	(16.3)	56.02	(183.8)	11.3	26,39

(a) NA indicates information is not available. - indicates no test results.
(b) Results of tests conducted with other initial speeds were corrected to this value with Eq. (28) of NBSIR 75-786 by assuming the same deceleration and the standard reaction time of 0.15s.
(c) Numbers assigned by author. Bicycle and testing details are given in Appendix Table Al. Postscript letters designate different brake pads or braking systems on the same bicycle. Small changes in wheel size (i.e., 1 inch) were not considered to constitute a different bicycle or a different braking system..
(d) Cr = chromium-plated steel. Al = aluminum alloy. SS = stainless steel. emb = embossed. serr = serrated.
(e) Data listed for Bike Nos. 117 through 121 are midpoints rather than averages.
(f) Ratio of wet-to-dry stopping distances.
(g) Material not identified.

aluminum rims provided substantially shorter stopping distances than the various kinds of steel rims, whether plated or not. In fact, of the seven bicycles tested with aluminum rims, six showed average wet stopping distances not exceeding 10.28 m (33.7 ft), which is the tentative criterion set forth in Section 3.3. By contrast, all but one of the bicycles with other rim materials exhibited average wet stopping distances which were longer than this; for many of them the wet stopping distances exceeded 18.29 m (60.0 ft). The one bicycle without aluminum rims that had a wet stopping distance less than 10.28 m (33.7 ft), Bike No. 108 A-Cr, had a dry stopping distance of only 3.05 m (10.0 ft). This implies a deceleration of 0.9 g, well above the pitchover threshold for many bicycles [2]. In general, the dry stopping distances tended to be slightly longer with aluminum rims than with steel rims although they were nevertheless acceptable (i.e., less than 4.57 m (15.0 ft)).

Looking at the data in a different way, it is seen that of the four bicycles with aluminum rims that were tested both wet and dry, three had wet-to-dry stopping distance ratios of less than 2.25. By contrast, no bicycle with another rim material had a wet-to-dry stopping distance ratio of less than 2.7.

As pointed out earlier, wet stopping distances of 10.28 m (33.7 ft) or less correspond to wet-to-dry brake friction ratios of 0.25 or greater. If, as the data suggest, brake friction ratios greater than 0.25 are achievable with aluminum-alloy rims, then Figure 3 shows that it is possible for the friction coefficient at the tire/pavement interfaces to affect stopping distance even when the brake surfaces are wetted. In the interest of achieving consistent test results, therefore, it would seem advisable to wet the pavement intentionally in order to avoid a situation where the first test is conducted on dry pavement and successive tests on increasingly wetted pavements.

Consider, now, the effects of embossing and serrations on the wheel rims. The data in Table 2 show that, on the whole, these treatments did not improve wet braking performance. This conclusion has also been put forth by a manufacturer, who found that "embossed rims showed no pronounced advantage and the most effective shredded the brake pads" [29]. Dimpling of rims has also been found to be ineffective in wet conditions [23].

5.2 Error Analysis

The variations in the wet stopping distances of bicycles with plain aluminum-alloy rims are given in Table 3 in terms of the observed ranges (or spreads) in the measured stopping distances. (Two of the bicycles listed in Table 2 with aluminum-alloy rims are not included in Table 3 because the data available for these two were inadequate to determine the ranges in the wet stopping distances.)

Table 3. Variations in Wet Stopping Distances

Caliper brakes, front and rear.
Plain aluminum-alloy wheel rims.
Initial speed, 24 km/h (15 mph).

Bike No.	No. of tests	Wet stopping distance average m	average (ft)	range m	range (ft)
107B	3	7.90	(25.9)	1.83	(6.0)
108A	10	6.06	(19.9)	0.32	(1.0)
108B	10	12.78	(41.9)	0.16	(0.5)
109[a]	3	7.53	(24.7)	3.03	(9.9)
109[a]	3	5.76	(18.9)	0.98	(3.2)
112A[b]	5	9.8	(32.)	1.8	(6.)
112A[b]	5	8.2	(27.)	1.5	(5.)
112A[b]	5	9.1	(30.)	1.5	(5.)

(a) The six wet braking tests of this bicycle with plain aluminum-alloy rims, reported in Table 2, were performed in two groups of three each, as shown here.
(b) The fifteen wet braking tests of this bicycle with plain aluminum-alloy rims, reported in Table 2, were performed in three groups of five each, as shown here.

The variations in stopping distance for the test series conducted with Bike No. 108 are exceedingly small, and may well constitute an example of what is attainable with good testing technique and careful attention to detail. The other test series listed in Table 3 exhibit wet stopping-distance ranges of approximately 1 to 3 m (3 to 10 ft) for series of three to five tests each. These variations are somewhat smaller than the random error estimate developed in Section 4.2 and suggest, therefore, that the test-to-test variability of the wet-to-dry brake friction ratio is not as large as had been estimated (i.e., ±0.05). On the other hand, the observed variations in wet stopping distance generally exceed those for dry braking tests performed with reasonably good testing technique* and thus provide evidence that the random variability in the brake friction ratio, while small, is not negligible.

An estimate of the lab-to-lab reproducibility of test results requires an assessment of the systematic errors involved in the test method. The available test results do not permit such an assessment since the different laboratories tested different bicycles. On the basis of the discussion in Section 3.3, however, it would appear that the systematic errors in wet braking tests may not be significantly different from those in dry braking tests. As shown in NBSIR 75-786, the probable overall range of the systematic errors is 1.24 m (4.1 ft) for the CPSC test method.** Most of this error band, specifically 1.05 m (3.4 ft), is attributable to allowed variations in test rider mass. In this connection it may be noted that wet braking tests carried out under ISO auspices call for all tests to be performed with the same total mass of bicycle, rider and onboard instrumentation [26,39]. This may be expected to lead to rather good lab-to-lab reproducibility for a given bicycle.

6. CONCLUSIONS

The study reported herein was concerned with riding tests to evaluate the wet-braking performances of bicycles having caliper brakes on both wheels. The kinetics of three different testing approaches were analyzed theoretically, relevant literature was reviewed, and available test results were critically examined. The following conclusions appear to be justified.

1. The stopping distances of bicycles are increased under wet-weather conditions because the friction coefficients at the brake surfaces and at the tire/pavement interfaces are reduced when wet.

* System C [2].

**System B [2].

2. The presence of water at the brake surfaces generally has a greater effect on wet stopping distance than water at the tire/pavement interfaces. On this basis it is recommended that road tests to evaluate the wet braking performances of bicycles should, if they are to be meaningful, include the wetting of the brake surfaces. With wet brake surfaces it is generally of no consequence whether or not the pavement is also wetted, unless the caliper brakes show a high degree of water resistance. In the latter instance, water at the tire/pavement interfaces can also influence the stopping distances. Since test pavements tend to become wetted due to water runoff from the bicycle wheel rims, it is further recommended, in the interest of reducing random errors in the test method, that the test pavements be intentionally wetted as well.

3. Aluminum-alloy wheel rims provide substantially better braking performance, when wet, than steel or chrome-plated rims. Embossing, serrating or dimpling of rims does not consistently improve wet braking performance.

4. A stopping distance of 10.28m (33.7 ft) is tentatively offered as a criterion for evaluating caliper-braked bicycles under wet conditions. This assumes a test method conforming to present CPSC requirements except for the wetting. At the present state of the art this wet stopping distance appears to be safely attainable only with bicycles having aluminum-alloy wheel rims. In other words, a conventional bicycle with steel wheel rims that could meet this wet braking criterion would probably exhibit excessive braking capability when dry.

5. The random variations in the wet stopping distances of bicycles are greater than the random variations that exist under dry conditions. The differences appear to be attributable to a test-to-test variability of the friction coefficients at the wet brake surfaces.

6. There is some reason to expect that the lab-to-lab reproducibility of wet braking test results may not be significantly different, for a given bicycle, from the reproducibility of dry braking test results. However, there are no test data available to confirm or refute this conclusion.

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APPENDIX

Table A1. Bicycle and Testing Details for Tables 2 and 3.[(a)]

Bike No.	Wheel size		Bicycle mass		Instrument mass		Rider mass		Initial speed		Handlever forces	
	mm	(in)	kg	(lb)	kg	(lb)	kg	(lb)	km/h	(mph)	N	(lbf)
101	660	(26)	19.1	(42)	9.1	(20)	88	(195)	14.7	(10)	180	(40)
102	690	(27)	18.1	(40)	9.1	(20)	68	(150)	14.7	(10)	180	(40)
103	510	(20)	16.3	(36)	NA		NA		14.7	(10)	(b)	
104	610	(24)	15.2	(34)	NA		NA		14.7	(10)	(b)	
105	660	(26)	17.4	(38)	NA		NA		14.7	(10)	(b)	
106	610	(24)	14.9	(33)	NA		NA		14.7	(10)	(b)	
107	690	(27)	16.3	(36)	11.2	(25)	74.8	(165)	24	(15)	180	(40)
108	710	(28)	32(c)	(71)	(d)		70	(154)	24	(15)	180	(40)
109	690	(27)	NA		NA		65	(143)	24	(15)	180	(40)
110	660	(26)	NA		NA		65	(143)	24	(15)	180	(40)
111	660	(26)	NA		2.3	(5)	69	(152)	24	(15)	180	(40)
112	690	(27)	NA		2.3	(5)	69	(152)	24	(15)	180	(40)
113	660	(26)	NA		(e)		88(f)	(194)	24	(15)	180	(40)
114	690	(27)	NA		(e)		88(f)	(194)	24	(15)	180	(40)
115	510	(20)	NA		(e)		88(f)	(194)	24	(15)	180	(40)
116	690	(27)	NA		(g)		(g)		24	(15)	180	(40)
117	660	(26)	(h)		(h)		(h)		24	(15)	180	(40)
118	660	(26)	(h)		(h)		(h)		24	(15)	180	(40)
119	660	(26)	(h)		(h)		(h)		24	(15)	180	(40)
120	660	(26)	(h)		(h)		(h)		24	(15)	180	(40)
121	660	(26)	(h)		(h)		(h)		24	(15)	180	(40)

(a) NA indicates information not available.
(b) Handlever forces were not limited.
(c) Includes instrumentation mass.
(d) Included in bicycle mass.
(e) Included in rider mass.
(f) Includes instrumentation mass.
(g) Total mass of rider and instrumentation was between 70 and 85 kg (154 and 187 lb).
(h) Total mass of bicycle, rider and instrumentation was 110 kg (243 lb).

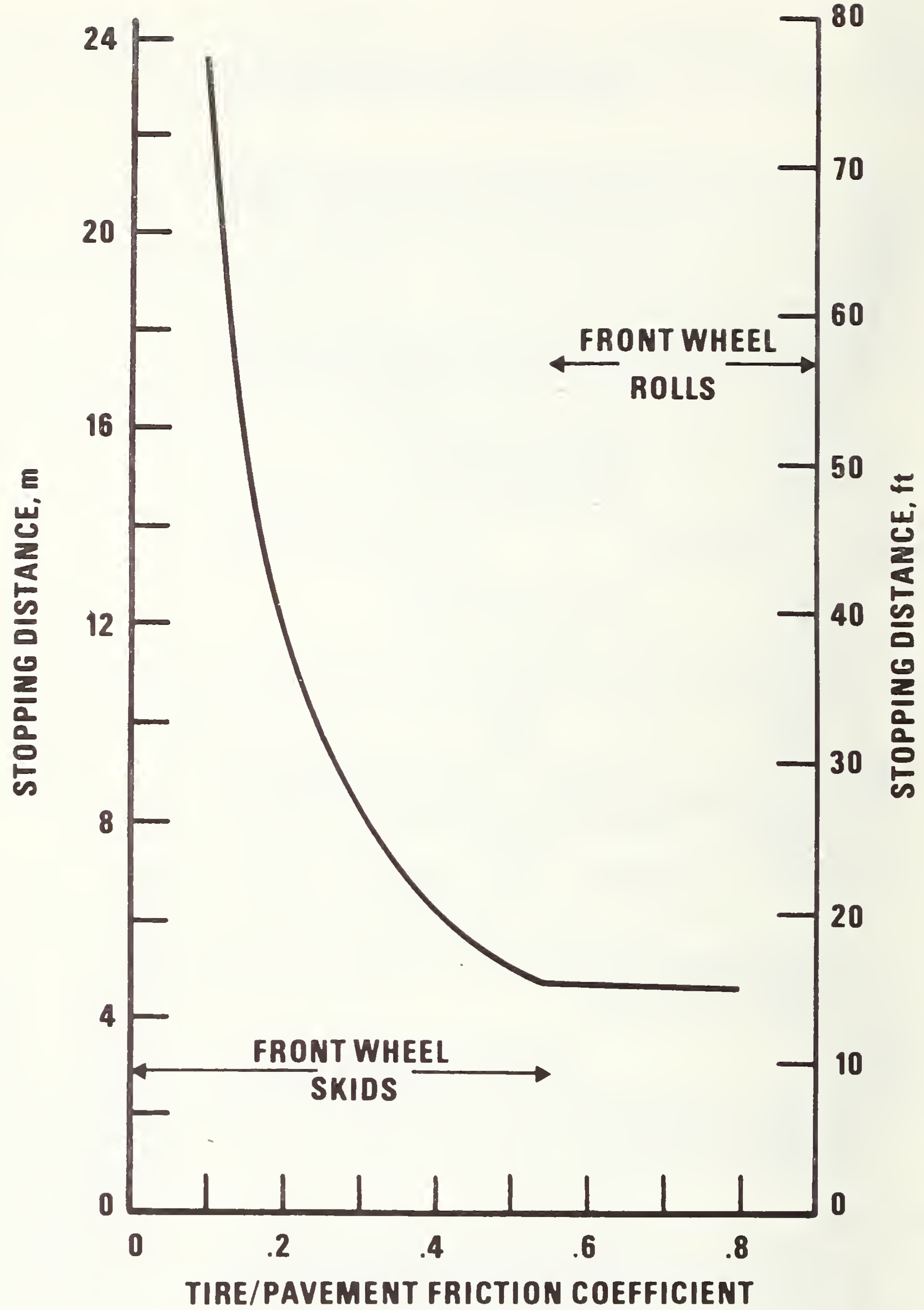

Figure 1. Effect of the tire/pavement friction coefficient on the stopping distance of a typical bicycle which has marginal braking capability under standard test conditions. The rear bicycle wheel skids without rolling throughout the range of coefficients plotted.

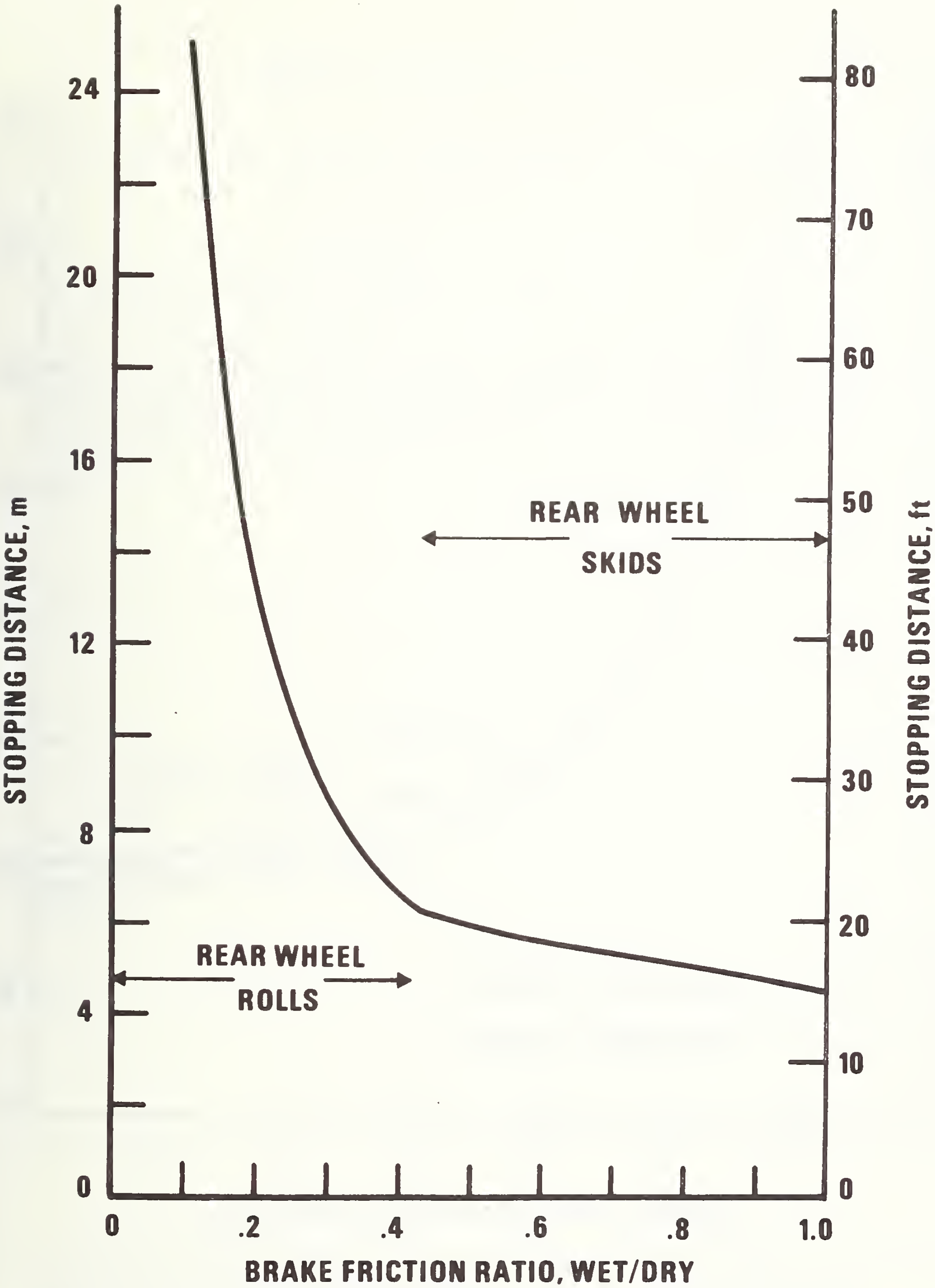

Figure 2. Effect of the wet-to-dry ratio of brake friction coefficients on the stopping distance of a typical bicycle which has marginal braking capability under standard test conditions. The front bicycle wheel rolls without slipping throughout the range of ratios plotted.

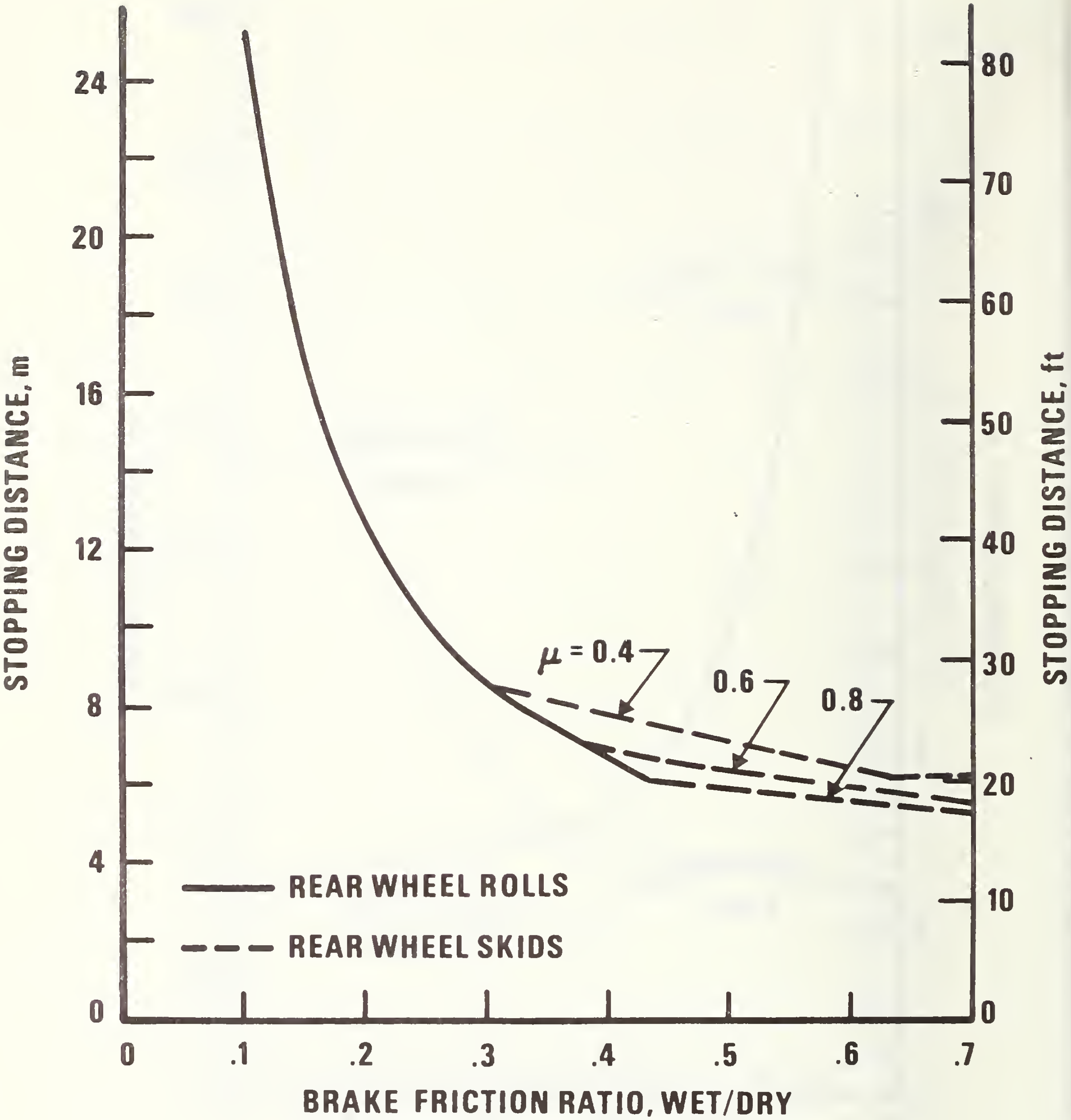

Figure 3. Combined effects of the tire/pavement friction coefficient (μ) and the wet-to-dry ratio of brake friction coefficients on the stopping distance of a typical bicycle which has marginal braking capability under standard test conditions.

Errata in NBSIR 75-786 [2]

1. In Equation 21, page 9, the parenthetical condition should read

$$f_f < \mu R_f .$$

2. Reference 5, page 46, should read

   International Organization for Standardization, Interim Report from WG1 on Criteria of Brake Performance Test as Agreed at the WG1 Meeting, February 1975, Document No. ISO/TC149/SC1 (Working Group 1 - 1) 38 (British Standards Institution, London, undated).

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The Consumer Product Safety Commission has expressed interest in the development of a riding test method for evaluating the braking performances of bicycles in wet weather. In this report three different testing approaches for caliper-braked bicycles are examined using kinetic analyses, a review of the literature, and an evaluation of available domestic and foreign test results. On the basis of the findings it is recommended that the riding test include the intentional wetting of both the bicycle brakes and the test pavement; the former to obtain meaningful results and the latter to enhance the repeatability of the test results. A tentative pass-fail criterion is also offered, based on a maximum wet stopping distance which, at this time, appears to be generally attainable only with bicycle wheels having aluminum-alloy rims. Error analyses of the test methods are presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Bicycles; brakes, bicycle; braking, wet; error analysis; friction, brake; friction, tire/pavement; kinetics, bicycle; measurements, bicycle braking; road tests; standards, bicycle safety; test methods, bicycle; wet braking.

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